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SPURIOUS ECHOES ON RADAR, A SURVEY

Vernon G. Plank

May 1959

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GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
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UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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SPURIOUS ECHOES ON RADAR, A SURVEY *

1. INTRODUCTION

With the advent of the modern radar which transmits powers on the order of megawatts and detects signals as small as 10^{-14} watts, there has been a marked increase in the number of spurious echoes received. Some are readily recognized as various types of man-made noise, or the result of anomalous propagation, but many of the others defy a simple explanation. Frequently these cause scope clutter or appear to be aircraft. On weather radars they confuse the important echoes from precipitation and clouds.

These spurious echoes are commonly called "angels." In the past they have been phenomena of mere casual interest; now they cause operational radar problems. On the positive side they provide the meteorologist with a new insight into the inner workings of the atmosphere.

Recent observations and accelerated research have contributed appreciably to our qualitative understanding of these elusive echoes. Controversy has by no means been eliminated, but certain features of the activity have been isolated and the general patterns established. This paper will review the more significant observations and discuss the present state of our knowledge or suspicions concerning sources.

2. PRE-RADAR OBSERVATIONS

The first angel echoes were detected with vertically-directed, pulsed radio equipment. In 1936, Sir Watson-Watt and others,[21] in England; R. C. Colwell and others,[4] in the United States; and S. K. Mitra,[16] in India, all reported detecting weak echoes at 3 to 300-meter

* A shorter, nondocumented version of this article was published in Electronics 31, 140-144, under the title "Atmospheric Angels Mimic Radar Echoes."

(Author's manuscript approved 4 February 1959)

wavelengths under conditions that suggested low-level atmospheric sources.*

Continued work during the period prior to the War supported the initial observations (for example, References 3, 6, 12, and 19).* In general, echoes were detected rather frequently from altitudes of 1,600-50,000 feet, during all seasons, both day and night. They tended to be especially strong during summer, during afternoon periods, and at altitudes below 8000 feet and near the region of the tropopause (the dividing region between troposphere and stratosphere). The altitude level of the sources appeared to vary with air mass and, on occasion, echoes that were strong and persistent at 25 and 50 meters were weak and intermittent at 3 meters. Maximum power reflection coefficients varied from 10^{-6} at long wavelengths to 10^{-10} at the shorter ones.

Considerable controversy existed concerning the source of these echoes. Pulsed radio antennas were, at best, only slightly directive and many people felt that the echoes were merely side reflections from ground objects. Others considered the sources to be refractive inhomogeneities in the form of layers or patches, primarily because of the many correlations between the occurrence and altitudes of the echoes and the meteorology. For example, strong echoes were received from altitudes where radiosonde and aircraft measurements showed the presence of weather fronts, air-cloud boundaries, and other strata having sharp and extensive lapse rates of relative humidity (refractive index is highly dependent on humidity). Weak and more diffuse echo types were observed with turbulent zones and thunderstorms. Ion layers had been suspected earlier but measurements did not support the hypothesis.[2, 14]

Various attempts were made to resolve this controversy, but general agreement was never reached. Nevertheless, the observations are most interesting when viewed in the light of subsequent radar observations of similar phenomena.

*This work has been reviewed by Plank.[1]

3. RADAR ECHOES FROM TROPOSPHERIC LAYERS *

Echoes from tropospheric layers or patches were first detected on vertical pointing radars in 1947 by Friend[32] at Harvard University, and Gherzi[34] in Shanghai, China. Friend operated 10-cm equipment and used radiosonde data to show that the echoes were derived from altitudes where atmospheric refractive layers existed. Gherzi observed echoes at 3 and 10 cm and, on one occasion, detected the same echoes at each of three wavelengths (3 and 10 cm and 13-17 meters).

Many layer echoes were subsequently reported. For example, Browne[30] detected low-level echoes at 10 cm over Cambridge, England and presented meteorological evidence to show that they were derived from an atmospheric subsidence inversion; Gould,[36] using .86 cm vertical-pointing equipment, received semicontinuous echoes for a 24-hour period from the clear sky over Fort Monmouth, New Jersey, and also from the near vicinity of a subsidence inversion; and Atlas and others[24, 25, 26] detected well-defined signals from sea breeze fronts at 1.25 cm and observed many echoes from invisible layers and thin stratified clouds at S and L bands.

The echoes and meteorological records obtained during the passage of a sea breeze front are shown in Fig. 1. That portion of the facsimile record at upper left, and all similar portions, show echoes received at fixed horizontal incidence from the front as it moved onshore from over Buzzards Bay, Massachusetts. The shoreline is at a range of 3000 feet; time is along the abscissa. Also, in the upper diagram, sandwiched between the horizontal incidence portions, are records for intervals when the radar was pointed vertically. No echoes were detected in the vertical until the front passed over the radar site; then the frontal surface itself gave the echoes shown at 800 feet altitude in the expanded scale portion at right. The other diagrams illustrate the variations in refractive index, wind direction, and temperature which occurred at an observation site located at that point where the

* The possibilities of radar scattering from ionospheric layers are sufficiently well known to require no comment.

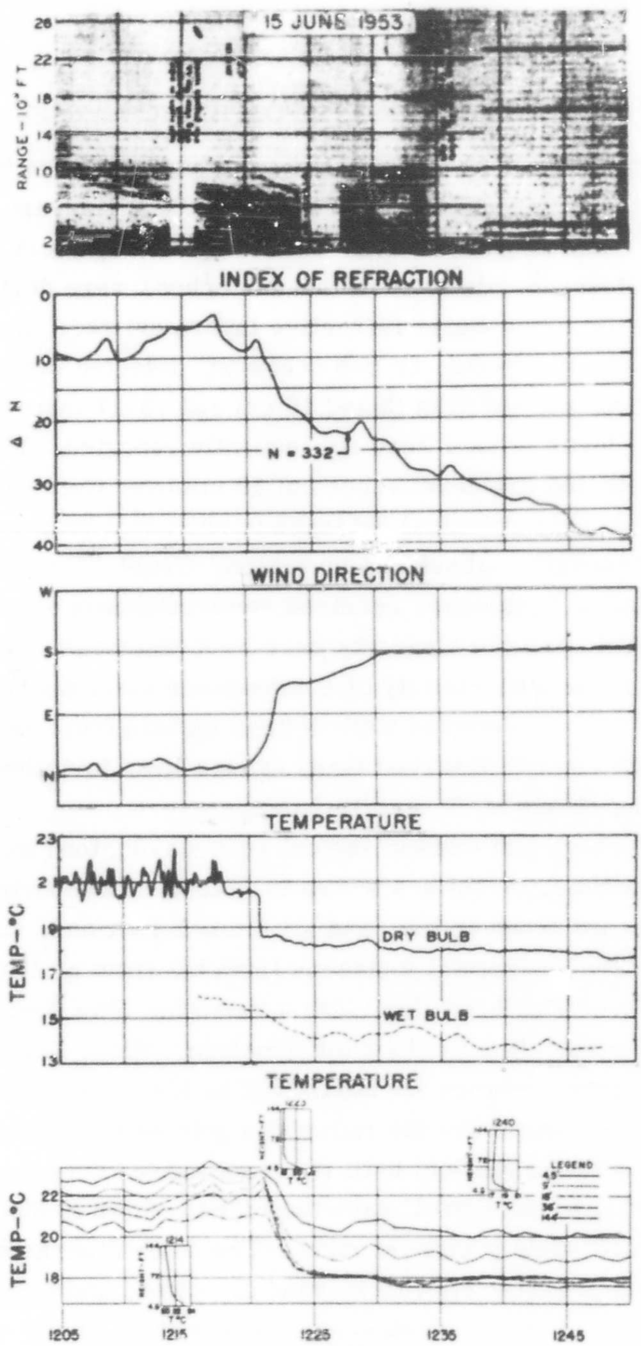

FIG. 1. Echoes and meteorological measurements obtained during approach and passage of a sea breeze front. (Courtesy of Dr. David Atlas, Air Force Cambridge Research Center.)

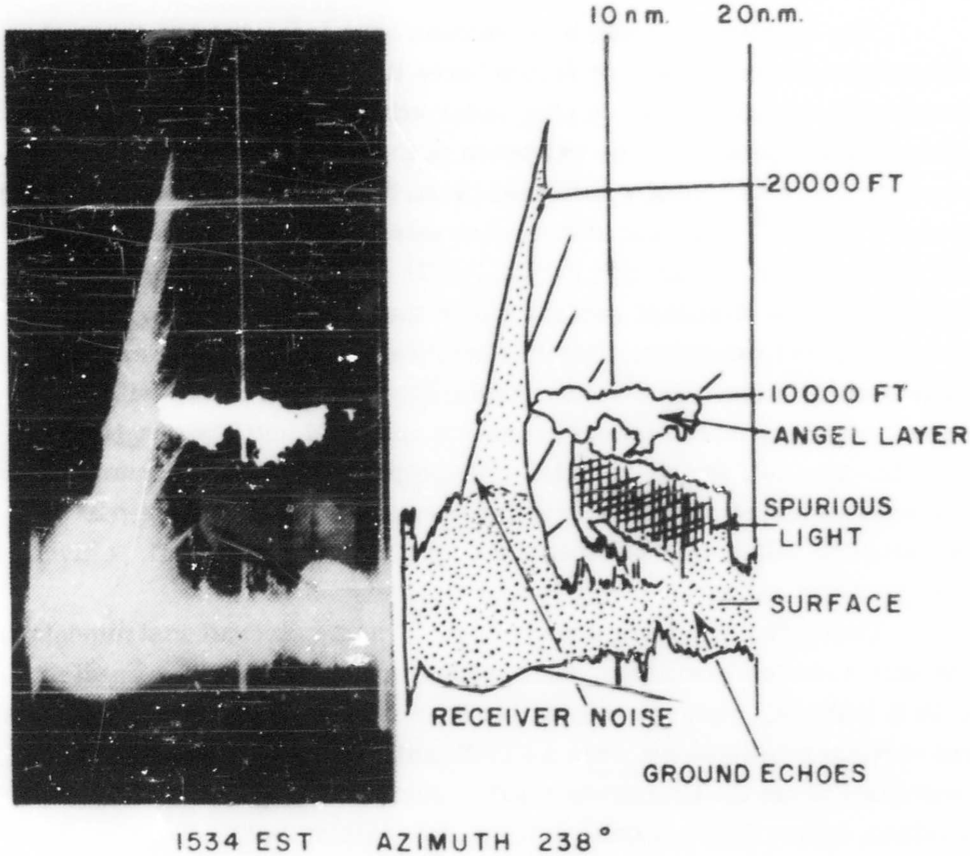

FIG. 2. Angel layer detected at S band. (Courtesy of Dr. David Atlas, Air Force Cambridge Research Center.)

radar beam crossed the shoreline. The temperatures shown in the lower diagram were measured on a tower at the altitudes indicated.

The photograph in Fig. 2 shows the 10-cm echo received from an invisible atmospheric layer. Film exposure was two minutes. A refractometer sounding made by an aircraft at the same time as the radar observations revealed that echo was derived from a region where the spatial refractive index variations were the most numerous and extensive.

The excellent correlations between echo locations and those of measured or known layers or fronts leave little doubt that certain atmospheric stratifications can give radar echo, even though proof has not been accomplished. The existence of the necessary refractive microstructure is strongly indicated by airborne refractometer measurements. Bauer,[27] utilizing slow ascent rates with a moderate response instrument and concentrating on the details of particular layers, has found numerous stratified regions where the refractive index variations were sharp and extensive. Regions extended over horizontal areas of many square miles, possessed considerable microstructure within the region, and evidenced vertical gradients up to 3 N units per meter[1] [$N = (n - 1) \times 10^6$, where n is the true refractive index]. Bauer has also shown theoretically that such layers can cause significant partial reflection of meter and centimeter waves and that, in general, a given layer is more reflective at the longer wavelengths.

Cunningham, Plank, and Campen,[31] using aircraft instrumentation with 1-meter resolution, have measured horizontal index gradients of 40 N units per meter in the visible boundary region of cumulus clouds and vertical gradients as large as 17 N units per meter in subsidence inversions along the California coast. Total change across these inversions ranges 30-70 N units within a few tens of feet.

Some echoes on radar may look like atmospheric layers but are merely side lobe reflections. Siting, antenna pattern, type of scan and set power and sensitivity are the determining factors. Very high power radars could be especially subject to such reflections, for even though the side lobes are 20 to 30 db below the main beam they still radiate substantial power.

4. ECHOES FROM WIND-CARRIED SOURCES

In 1943, Baldwin[38] reported a different type of radar echo phenomena. Shortly thereafter, similar observations were noted by others.[32, 43, 45, 47] Invisible objects in the lower troposphere at

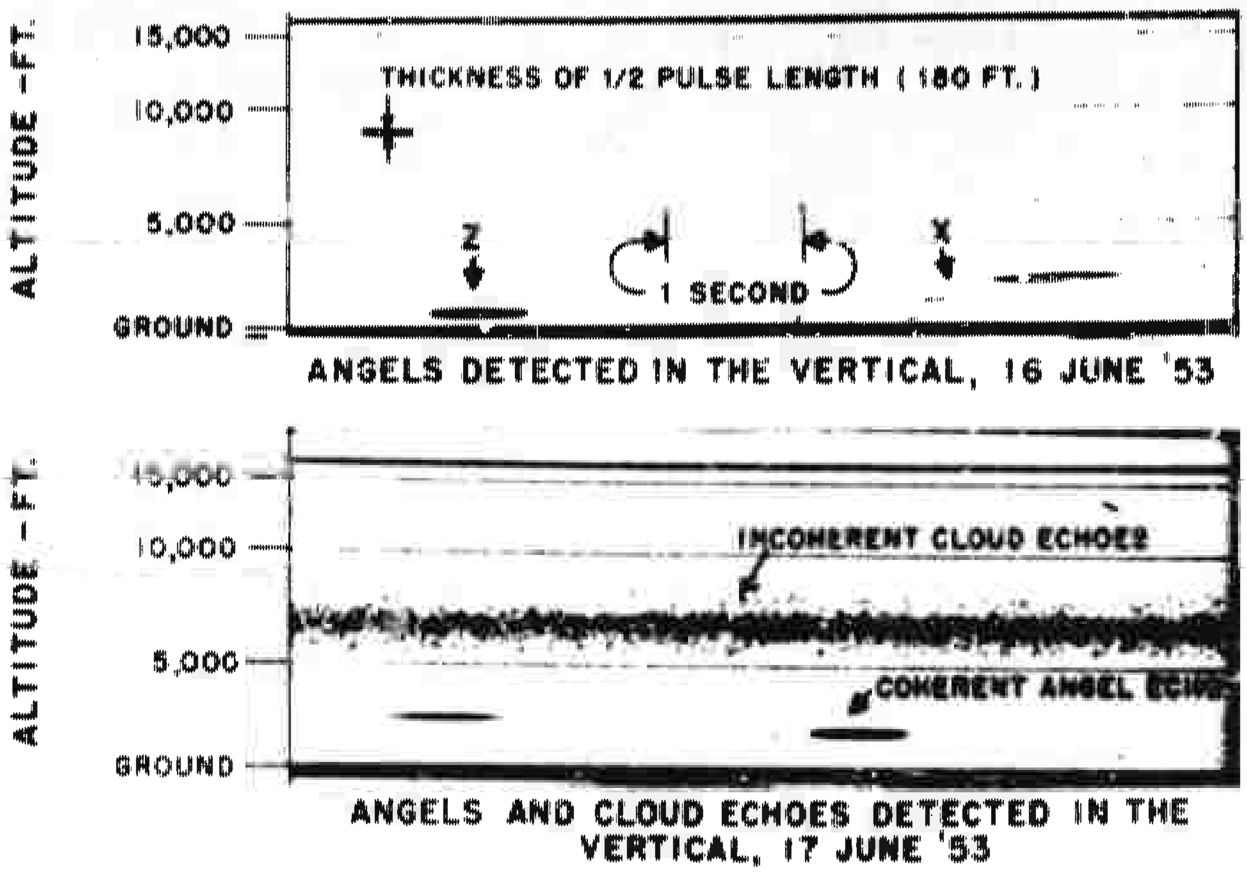

FIG. 3. Photographic record of angel and cloud echoes obtained by moving film continuously past the A/R scope of a 1.25-cm vertical-pointing radar. Time is along the abscissa. X and Z differentiate two sizes and intensities of echo.

ranges up to 20 miles were causing transitory and sharply localized echoes on sensitive X- and S-band equipment. Most of the objects seemed to be carried by the wind. When observed on the PPI scope, the echoes took the form of dots or small areas, moving over the face, sometimes in tremendous numbers. On an RHI scope or on the A/R scope of a radar with its beam oriented between horizontal and vertical, the echoes were of short duration, lasting a fraction of a second to several seconds (see Fig. 3). Frequently, a number of them occurred simultaneously at different ranges. Their character was coherent — quite different from the scattering signals from precipitation. Most

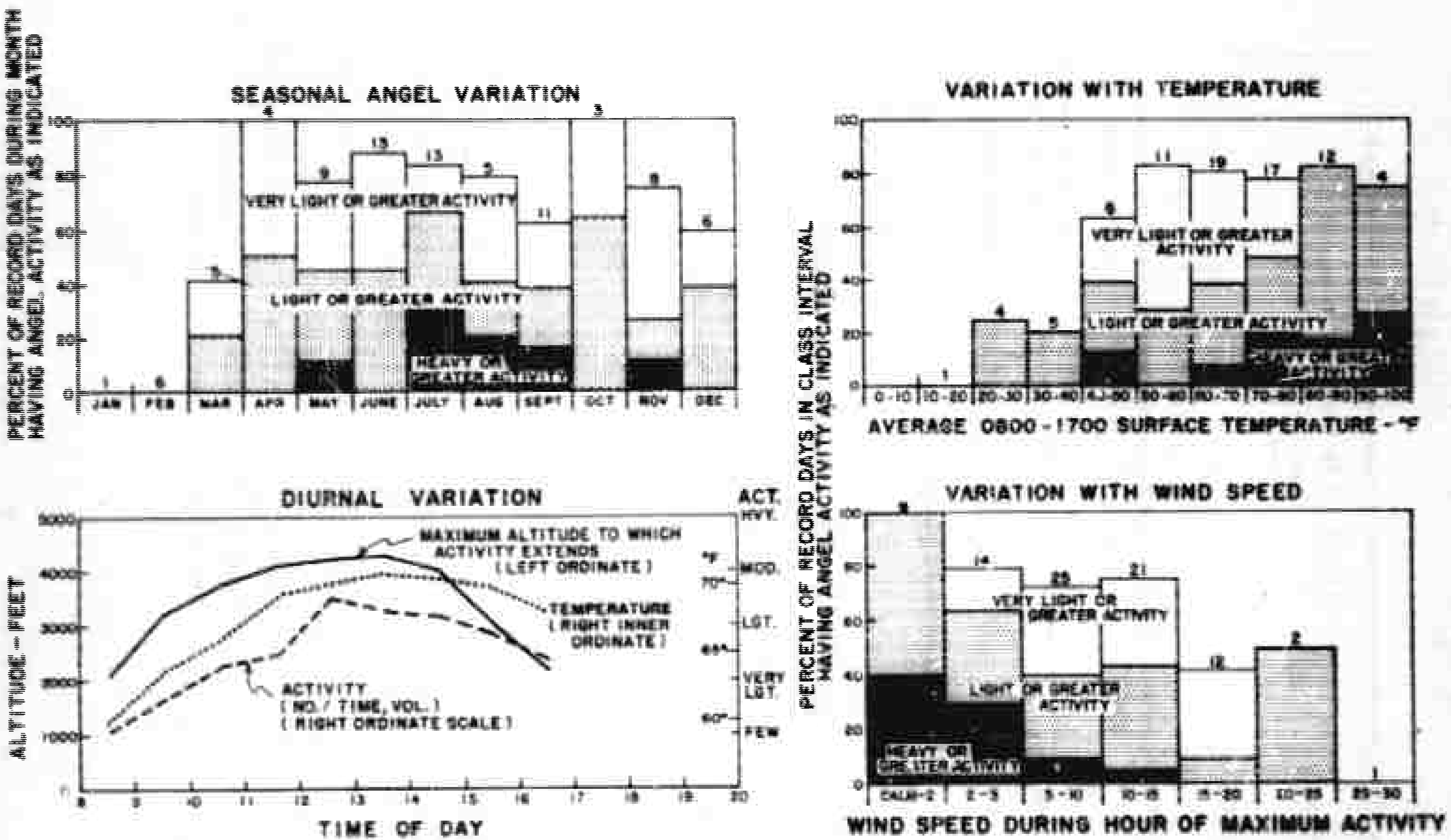

FIG. 4. The dependence of angel activity on season, time of day, temperature, and wind speed. Three degrees of activity are differentiated on the basis of the number of echoes per 500-foot height interval per 5 minutes as very light 6-20, light 20-42, heavy > 42. Numbers above bars are total number of days of record in month or class.

sources were indicated to be smaller than the resolution capability of the radar.

Many such echoes have since been detected, especially at Q, K, and X bands (for example, References 1, 40, 52, and 57). Maximum volume reflectivities range from 10^{-10} to 10^{-12}, or about 0.4 to 50 cm^2 radar cross section. Knowledge of the specific seasonal, diurnal, and meteorological dependence of the echo activity is limited, but the results of one study of 1.25-cm vertical-pointing observations are probably indicative.[1]

This investigation revealed that angels occur primarily on days with high temperature, high humidity, and low wind speed. Activity was especially intense during the summer months, during midday, and with clear skies. (See Fig. 4.) Activity also appeared to be favored by opposing conditions of surface and atmospheric moisture. No angels occurred when the ground was completely covered with snow, when low-level atmospheric temperature inversions existed below minimum radar range, or at times when the atmosphere was extremely dry.

In most instances angels occurred entirely within the convective mixing region, sometimes showing an obvious, intimate correlation with convective (cumulus) clouds. On clear days there was a pronounced diurnal trend; echoes beginning in the morning (6 - 9 a.m.), increasing to maximum number at local noon, then decreasing rather sharply during the afternoon. The altitude to which echoes extended rose throughout the morning, was highest at the time of maximum temperature (about 2 p.m.), and dropped off thereafter.

Bunched or layer echoes occurred in the vicinity of sharp moisture gradients, in association with or sometimes immediately after a summer rain, or under conditions of extremely high moisture content (greater than 12 gms of water vapor per kg of air).

Calculations indicated that the size of the echo sources ranged from 0 to 70 feet in horizontal dimension and from less than 180 to greater than 360 feet in vertical dimension. Small sources were more numerous than large ones.

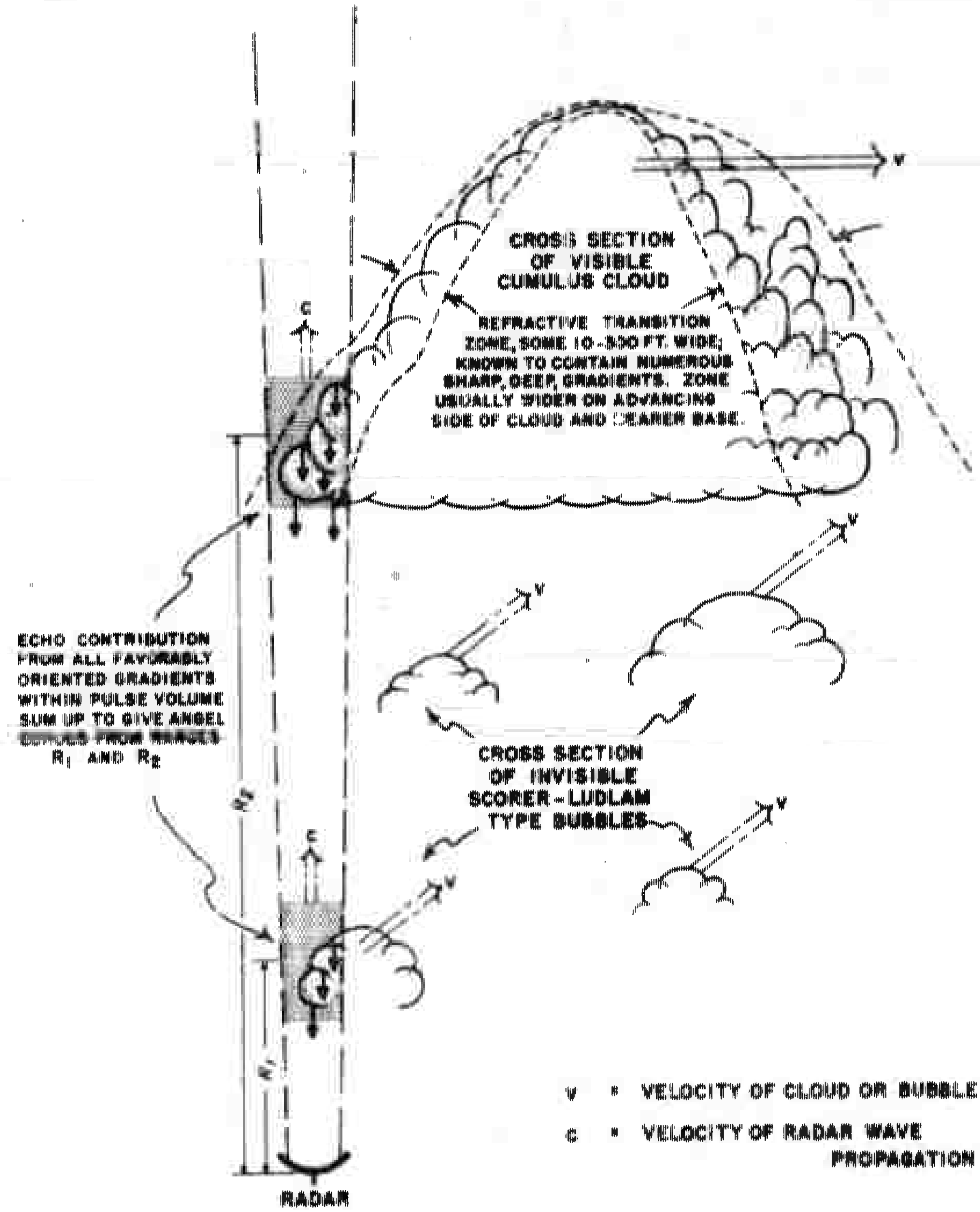

FIG. 5. Sketch of a visible cumulus cloud and invisible Scorer-Ludlam bubbles and their gross refractive radar characteristics. A possible method whereby angel echoes could be derived from the boundary regions is illustrated.

The primary source of these echoes is believed to be refractive index inhomogeneities of various types; for example, convective bubbles, highly refractive portions of atmospheric layers, and water vapor and or temperature anomaly regions. The precise mechanisms of energy return from a variable dielectric is unknown, but it is suspected that echo is the summation product of backscatter from all the favorably-spaced-and-oriented microregions of nonuniform refractive index gradient within the pulse volume (as illustrated in Fig. 5).

The inhomogeneity that appears most capable of explaining day-time activity is the convective bubble. Such invisible bubbles rise from near the earth's surface during periods of active solar heating and are important elements in the process of cumulus cloud development and growth. The sharp refractive gradients present in the upper and side boundary region of the bubble are believed responsible for echo. Focusing effects may contribute. Aircraft, glider, and other observations verify the existence of these bubbles, and theory forecasts the sharp boundary structure.[61] (These observations are summarized by Plank.[59]) In the investigation previously cited, those meteorological conditions favoring the existence of refractive index anomalies and the theoretical refractive properties of nonsaturated air parcels rising through a turbulent environment were also established. The observed seasonal and temperature dependence of angels was found to agree nicely with the theoretical conditions favoring refractive inhomogeneities, and virtually every observed feature of the activity was explained under the assumption that the responsible inhomogeneities were rising parcels of warm-moist air; that is, convective bubbles.

Insects are also important contributors to this angel activity. Their detection on sensitive, high resolution, Q-, K-, and X-band radars has been verified, both observationally[76,85] and theoretically.[1] Radar cross sections range up to four times geometric size and, since the radar collapses a very considerable portion of the atmosphere on to a small indicator, surprisingly few insects cause appreciable scope

clutter. On sets such as the 0.86-cm TPQ-6 (Cloud Base and Top Indicator), only one detectable-size insect per hundred thousand cubic feet is required to fill the scope with return. Normal atmospheric concentrations of large insects range some four to six orders of magnitude less than this but at times, such as the spring and fall periods of swarming and migration, they may approach and even exceed it.

The available information concerning habits and concentrations of insects in the lower atmosphere reveals that insect and angel activities are very similar in many respects.[1] However, with few exceptions, insects do not fly at temperatures below 40°F or above 95°F. Substantial angel activity is observed on both sides of these limits. Also, the indicated angel-source sizes of some tens of feet are not readily explained by insects.

On occasion, large mineral and organic particles are carried into the air by storm winds, thunderstorms, and fires. During the period of their settling, these particles may also cause angel echoes.[50, 51, 85] Another source is "chaff" or "window."[81] This material is sometimes released from aircraft during special studies.

The relative importance of the two primary sources depends on location, time of day, and wavelength. Indications are that inhomogeneities are more important in humid climates, during midday, and at the longer wavelengths, other set characteristics being equal. Insects predominate in arid climates, toward evening, and at the shorter wavelengths.

There have been several attempts to artificially create refractive inhomogeneities that would scatter sufficient energy to account for angels of this type. Crawford[76] formed steam clouds and allowed them to drift across his antenna beam and also flew a B-25 aircraft through the beam to see whether the turbulent exhaust gasses would be detectable. In neither case was a signal observed. More recently, Tolbert et al[35] measured the backscattering cross sections of helium-filled soap bubbles and steam clouds. They received no measurable signal

from the steam and only very small signal from the bubbles. They concluded that it would be very difficult to get a return on millimeter radar from refractive index gradients.

Although such experiments are interesting they are hardly conclusive. The model is a single gradient region or a small inhomogeneity when what is required is several million bubbles or inhomogeneities that occupy an atmospheric volume the size of the pulse volume.

5. ANGELS INDEPENDENT OF THE WIND

There is also a class of localized-source angel activity which is quite similar in scope appearance to that from the wind-carried sources, except that the echoes move at velocities different from the wind velocity and in directions that may or may not agree with the wind direction or be consistent for all echoes.[37, 38, 66] Generally, velocities are under 50 knots, movements are semiregular, and the tracks are smooth gentle curves.

Such angels have been observed primarily on the PPI scan of air traffic control radars with MTI, and they strongly resemble the echoes from small airplanes or helicopters. They usually occur at ranges less than 20 miles and sometimes are so prevalent that they constitute a definite operational handicap, as may be seen in Fig. 6. L-band radars are most strongly affected, but the echoes are not uncommon at S band and have been reported at X band. On several occasions, the sources have been tracked for periods up to 20 minutes.[38, 43] At L band, the radar cross sections range as large as 700 cm^2.[37]

Suggested sources for the major part of this activity are birds, certain of the larger, more rapidly flying insects, and elevated inhomogeneities of refractive index. Birds are excellent scatterers and, at close range, can cause substantial echo on many radars.[77, 82] Lack[79] reported radar cross sections as large as 20 cm^2 at S band. Other measurements show that sea gulls scatter energy as though they were quarts of water moving through the sky.[83] Large birds at 10 miles range will give signals equivalent to those from a medium size aircraft

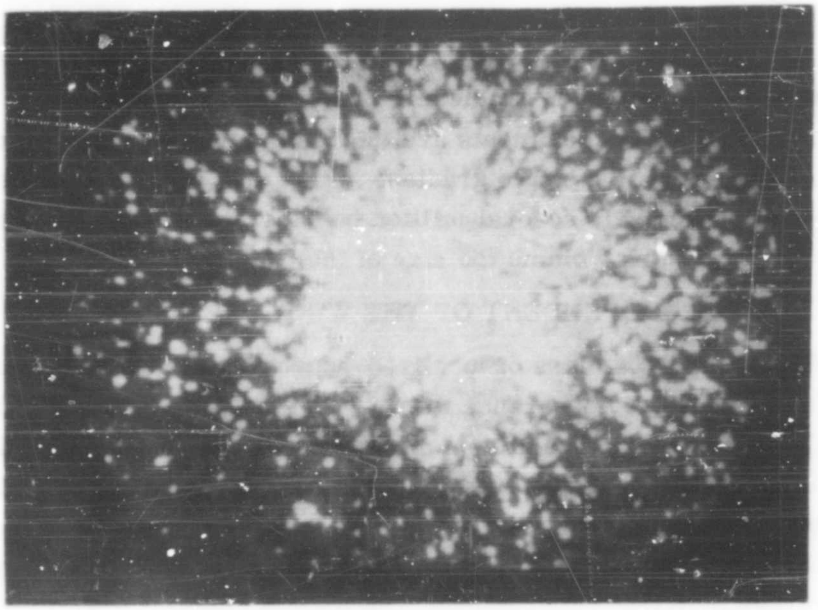

FIG. 6. A large swarm of angels during clear weather on an S-band radar operating on low beam with MTI. Total range is 15 miles. (Courtesy of Mr. J. M. Gray, Airborne Instruments Laboratory.)

at 50 miles.[75] In fact, even the fading-fluctuation character of the echoes resembles that of aircraft.

Birds are reported to be almost wholly responsible for the angel activity observed near shore over the Atlantic Ocean in mid-latitudes. Their echoes vary in number, depending on day and location, out to ranges of 20-25 miles. Many birds have been observed visually at places that agreed with echo positions. Also, the angel velocities and motions are appropriate to birds, and the presence and patterns of activity conform with many of their characteristic habits. Echo strengths are enchanced by the elevation of birds above the surface and because birds frequently fly in flocks. As few as eight birds per square mile can completely fill a PPI scope with return.[83]

Birds probably predominate as sources of wind-independent angels, but the character, size, and signal strengths of certain echoes

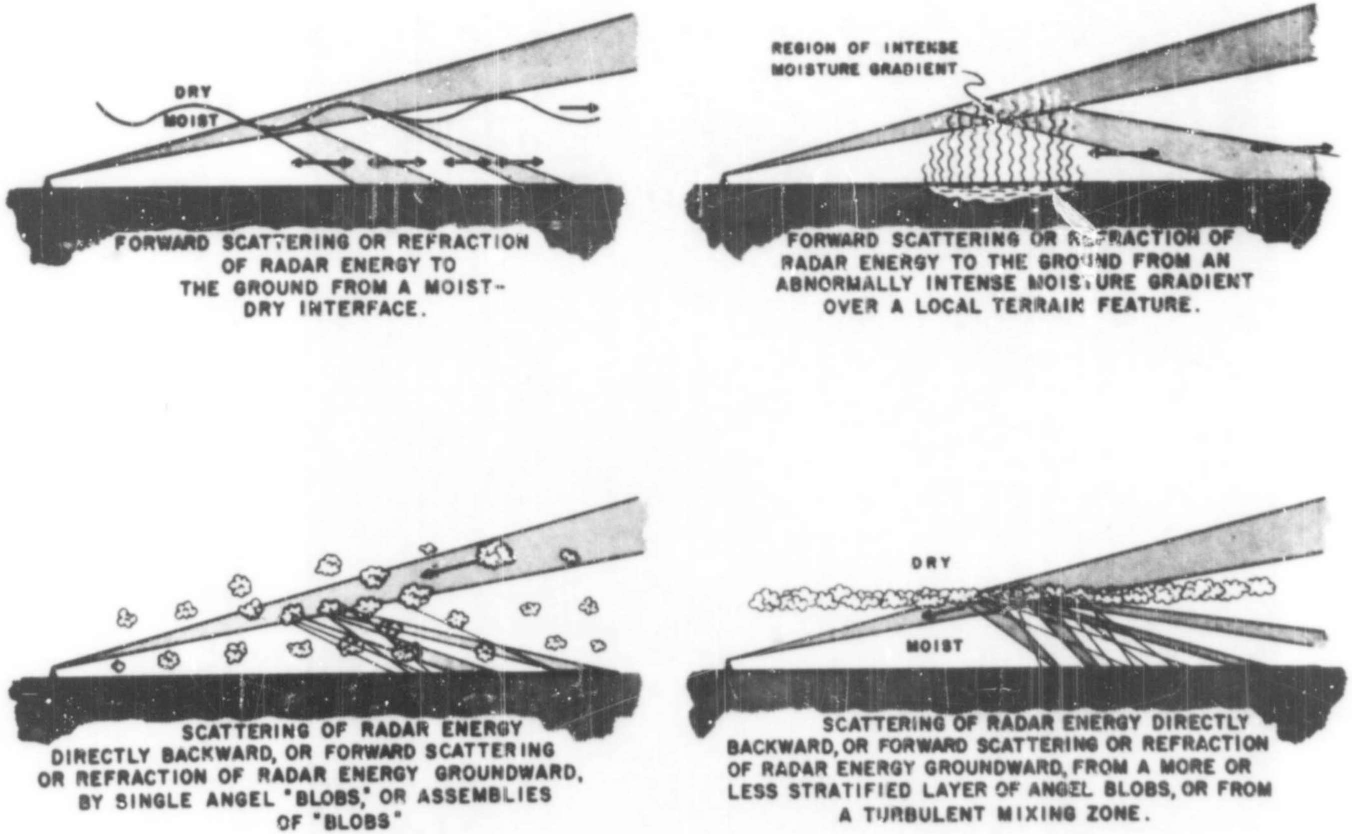

FIG. 7. Possible sources of unusual anomalous propagation. If only a portion of a layer or a few "blobs" are effective, then the scope echoes may be fairly discrete. If different portions or blobs are effective on successive antenna scans, then echo patterns of apparent rapid motion may occur.

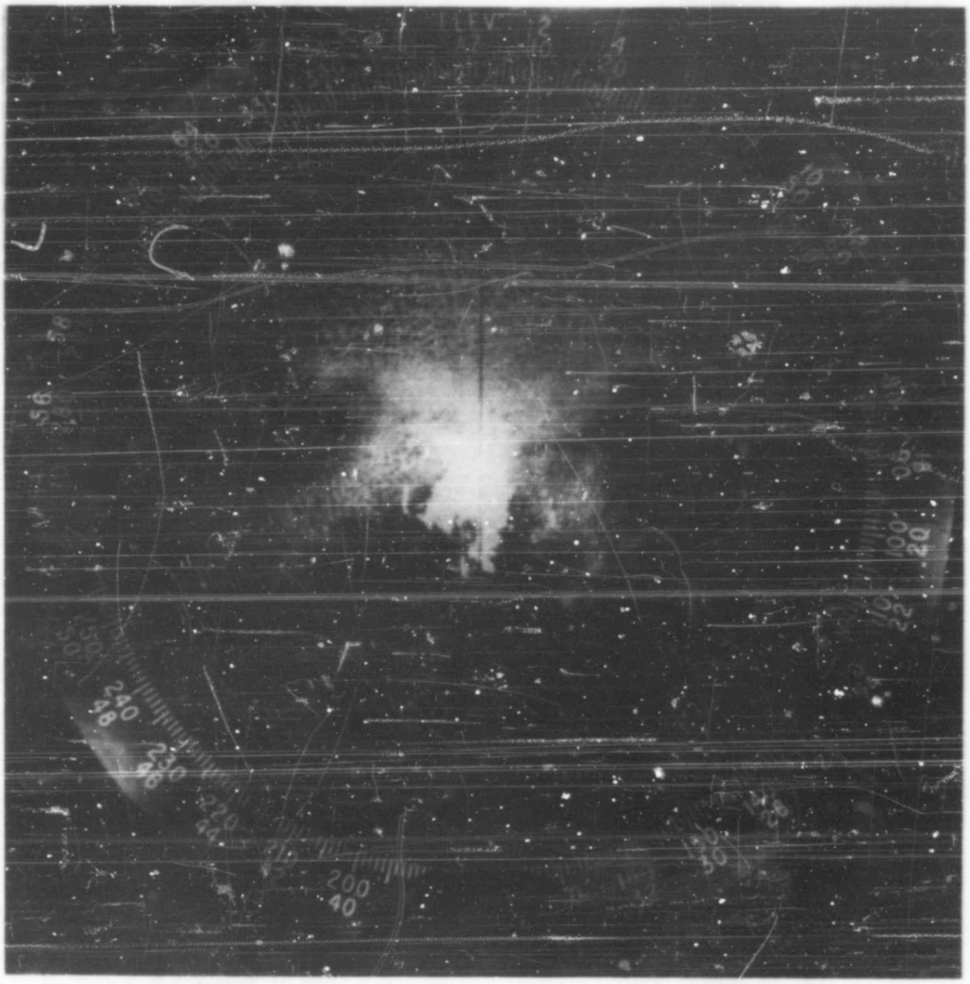

FIG. 8. Anomalous propagation on a clear day at 3.2 cm. Total range is 100 miles. (Courtesy of Dr. David Atlas, Air Force Cambridge Research Center.)

require other sources (for example, References 37, 44, 63, 67, 68, 71, and 73). One source is elevated refractive layers or inhomogeneities. In this case, the inhomogeneities play a different role from that described previously; namely, they divert energy to ground. The inhomogeneities are portions of laminar or turbulent atmospheric layers, properly-structured and oriented "blobs," or convective bubbles. They deflect energy to ground by refractive bending or forward scattering. The illuminated patch of ground, perhaps a particular terrain feature, then scatters energy back to the receiver via the reciprocal path. The situation is really anomalous propagation, but only a relatively few atmospheric volumes of small size are involved. Echo movement results both from the movement of the volumes and from changes in their patterns in time and space. The various possibilities are illustrated in Fig. 7.

The influence of anomalous propagation at 3 cm resulting from convective "blobs" on a clear sunny day at Salina, Kansas is shown in Fig. 8. Major terrain features are vaguely indicated on the PPI and, in the clear areas to the southwest, fixed discrete echoes are associated with towns beyond the normal horizon, out to 80 miles. This behavior has been analyzed by Atlas,[64] who concludes: "Although it is still questionable, the most reasonable explanation appears to be forward scatter from the eddies to the ground and back again, the forward scatter signal from the 'blobs' being much greater than the back scatter.[65] In this manner, relatively featureless terrain would present a pattern of the elevated 'mirror' through which it is viewed by the radar."

Sensitive L-band radars may detect echoes from the aurora borealis or aurora australis.[44] Multiple sweep reflections from the dense ion clouds and streamers which are located at high altitudes above the magnetic poles will appear on the scope at any range as discrete echoes or echo areas; and they may move slowly or rapidly, consistently or erratically. Aurora echoes are discussed more fully in Section 10.2.

Other possible explanations for wind-independent echoes are: sidelobe and second sweep echoes, reflections from automobiles, instrumentally-produced signals, interference between radars, and

various types of man-made noise. According to Ligda,* one source of false echoes near the edge of "weather-radar" scopes is slight reflection of the electron beam from the sides of the cathode-ray tube when strong precipitation echoes exist just beyond a scope range.

6. ANGELS ASSOCIATED WITH CLOUDS

A different and much larger wind-carried echo source has been described by Harper, Ludlam, and Saunders[49] and Atlas.[24, 25] Echoes that defined the general upper and side boundary region of small cumulus clouds were received at S band at East Hill, England and Cape Cod, Massachusetts.** The clouds were nearby and clearly visible, and a one-to-one correspondence was established between the echo and cloud positions. Droplet distributions in the clouds were such as to preclude a signal from particle scattering. On the RHI scope, the "mantel" or "cap" echoes looked like inverted U's and V's, as in Fig. 9.

These echoes undoubtedly result from the back-scattering of energy from the numerous refractive-index inhomogeneities that are present in the boundary region.[31, 58] The most favorable condition for echo occurs when the region is thin and when there is a large index difference between cloud interior and the clear air surroundings. This exists when clouds are moving actively upward into very dry air. The cross-sectional shape of the boundary region is shown in Fig. 5, page 10. It can be seen that it is an inverted U.

The Harper-Atlas observations also revealed the presence of other angel echoes rising into the mantels (cumuli) from the clear air region below, and sometimes columnar echoes were observed extending from the ground to the mantels. Implications are that the radar was "seeing" convective bubbles and thermals.

Certain echoes received from cloud and weather areas have a character distinctly different from precipitation return (for example References 68, 71, and 73). Most are very sharply defined but occasionally they are diffuse and indistinct, sometimes arranged in bands. Usually they cover areas as large or larger than the typical precipitation

* M.G.H. Ligda, private communication.

** Neither Harper nor Atlas detected the mantels at X band, but they have subsequently been reported by Ligda.[53]

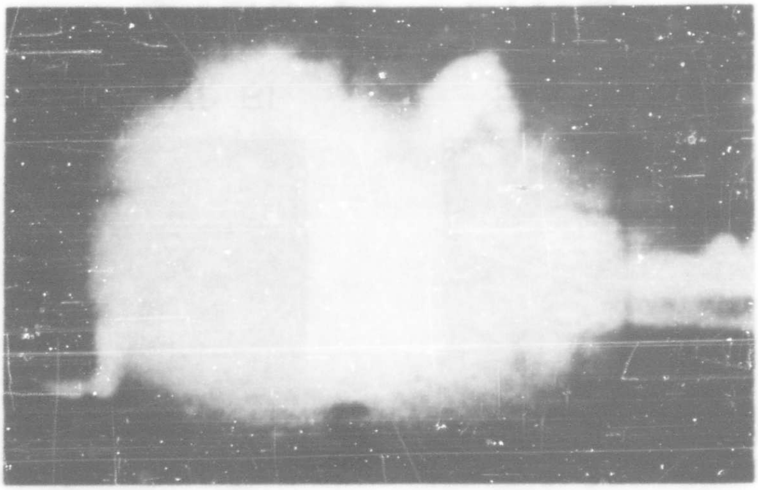

FIG. 9. Mantel echo on the RHI scope of a 10-cm radar at 4 miles range and 5000 feet altitude. The circular echo beneath the inverted "U" of the mantel is ascending at a rate of 250 feet per minute. (Courtesy of Mr. W.G. Harper, British Meteorological Office, London.)

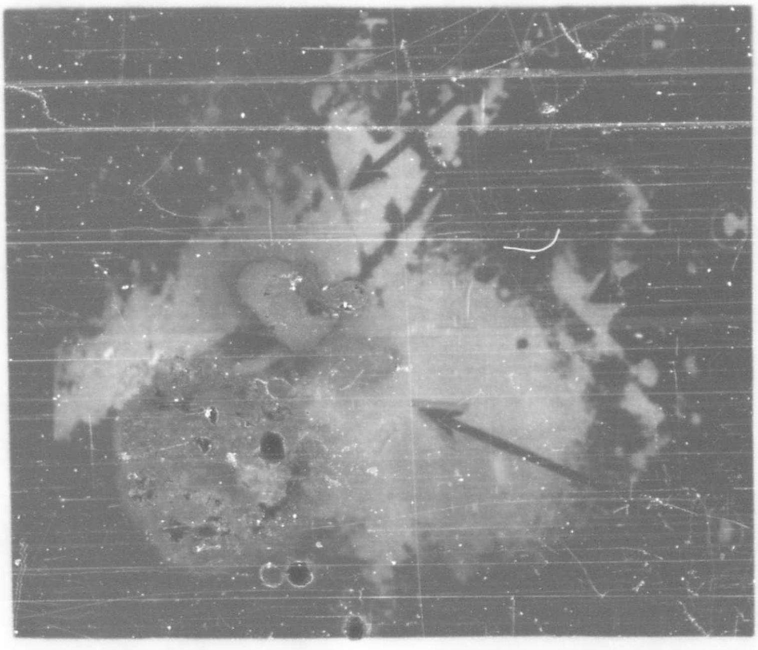

FIG. 10. Echoes from a "precursor line." Precipitation echo from the squall line is shown at A. The precursor line is B. C and D are air mass showers and ground clutter, respectively. S band. Total range is 150 nautical miles. (Courtesy of Dr. M.G.H. Ligda, Stanford Research Institute.)

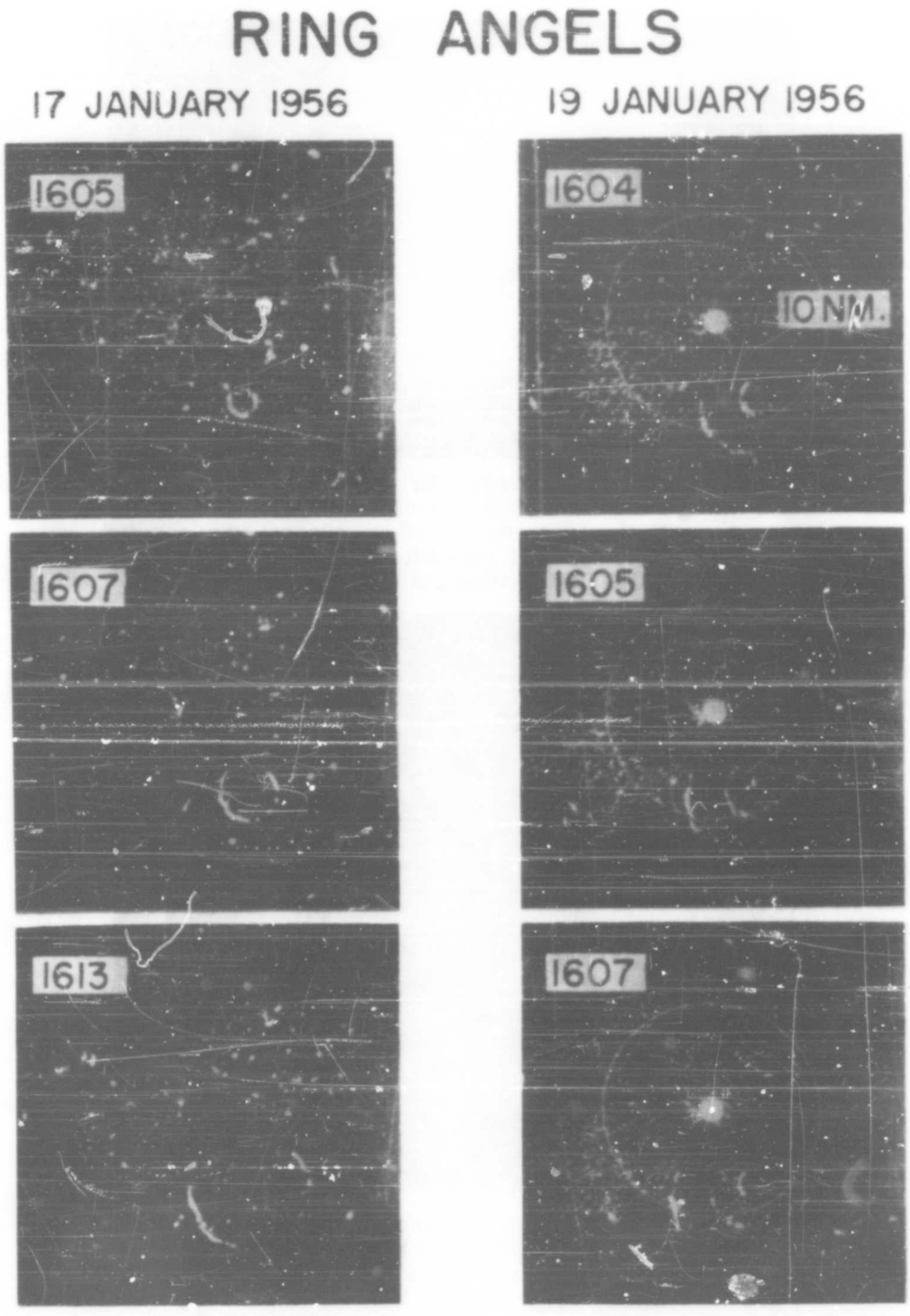

FIG. 11. Ring echoes observed on two January days at 23 cm with MTI. Total range is 20 miles. (Courtesy of Mr. F. C. Elder, University of Michigan.)

cell echoes seen on "weather-radars," have radial patterns, and occur at places not normally associated with precipitation. Frequently they appear very suddenly, and individual elements of the echo show little movement. The general pattern of echo may, however, move quickly and/or erratically. Invariably, there is a lack of agreement between the presence or location of the echoes on two radars covering a common area. Favored places for echo are behind fast-moving cold fronts and squall lines. Sometimes "dry" squall lines are detected; that is, there are no clouds or precipitation associated with the line (Ligda[53]). Other times precursor lines ahead of the squall line give a sharp distinct echo. Such precursors are also devoid of scattering particles. Leach[54] has made an extensive study of such lines and has concluded that they are either gravity waves or the "nose" portion of an "undercutting" weather front. Figure 10 shows a precursor-line echo.

Much of this activity results from localized anomalous propagation due to the many refracting-ducting regions within the cloud complex and their changing patterns in time and space. Forward scattering to ground and direct back scatter from inhomogeneities at cloud boundaries also contribute to this activity. Various combinations can occur and cause complicated effects. Extending the Atlas analogy, the scope patterns are composed of terrain features viewed through a large badly-warped mirror with many holes, which is oriented quasi-horizontally and inverted. The surface quality of this mirror is very heterogeneous, with many tarnished spots that scatter energy.

7. RING ANGELS

The echoes in Fig. 11 were detected at Ann Arbor, Michigan at L band using MTI.[42] In appearance the echoes are similar to waves formed by dropping an object in water. The echoes originated as intense point sources and expanded outward at average radial velocities of 52 mph. Successive rings were separated by 3-5 minutes in time and had a typical radial spacing of 3 miles. The source point and all rings formed from it seemed to move with the prevailing wind. Expansion rates were the same in all directions but they decreased with

increasing radius. As many as three rings were wholly or partially present on the scope at one time.

These echoes were observed in all seasons but were most frequent in winter. Associated weather ranged from clear to moderate snow. The preferred time of occurrence was from 1450 EST until radar observations terminated at 1700 EST. They formed in seven different areas, but four were favored. Occasionally, several sources produced rings at the same time.

An aircraft reconnoitered those places of most frequent occurrence and once rings were detected from the same area where the aircraft was flying. Nothing unusual was observed; no odd topographical features, no large industrial establishments or heating plants, and no obvious sources of radiation. The terrain was slightly rolling, composed mostly of farm areas with occasional wood plots.

Ring echoes may be derived from point source gravity waves. Quite analogous to the manner in which water waves occur at a water-air boundary, it is also possible to have internal atmospheric waves occur at the transition zone between two horizontally-stratified layers of air having different density. A common situation is that warm-dry air lies over cool-moist air. In this case, the refractive index of the layers is also distinctly different. That gravity waves can at times give radar echo is strongly indicated by the studies of Leach and Ligda.[54]

Using the observed spacing between rings and reasonable assumptions about the atmospheric situation, the calculated rates for the expansion of gravity waves are the same order as the expansion rates observed. Thus, the echoes may be the result of back scatter from an elevated circular wave or the wave may serve as a means whereby radar energy is scattered forward to ground, similar to the situation illustrated in the upper left sketch in Fig. 7, page 15. Either explanation is possible but, as noted by Elder,[42] it is difficult to visualize the mechanism of wave generation and to account for echo at those places where the radar rays are parallel with the elevated wave front. The

possibility that a sudden penetration of the interface by an aircraft or a growing cumulus cloud might trigger wave trains is not too attractive. A strong periodic source is required to explain concentric rings. The final explanation must await additional evidence.

At Texarkana, Arkansas, another type of ring echo has been observed and ascribed to red-wing blackbirds (Fig. 12).[80] Thousands of birds flying out from a common roosting ground a few minutes before sunrise show up on the PPI as an expanding ring which grows broader and more diffuse with time until the composite echo breaks into individual ones and fades at radii of 12 to 35 miles. Sometimes weak irregularly-shaped echoes can also be seen in late afternoon as the birds leave their feeding places and converge toward the roosting ground. The morning rings have been observed on many occasions, all emanating from the same spot at very nearly the same time. Ornithologists state that the spot is a unique roosting ground for all the blackbirds over many hundred square miles.

That the Michigan rings may also be caused by birds is extremely doubtful. The Michigan rings are better defined and more regular. Besides, they have a periodicity of 3-5 minutes and the source center drifts with the wind. The requirements imposed on bird flocks to satisfy these observations are so stringent as to be scarecly credible.

8. RAPID AND ERRACTIC MOVEMENTS

Very rapid and/or erratically moving angels have also been reported (for example, Reference 69). There is a type of nonaircraft echo that suddenly appears, moves for a matter of minutes in a semi-straight line path at velocities of some 600-2000 mph, and then disappears. Certain of these echoes may be caused by the aurora borealis mechanism described in Section 10.2. Another source might be shock waves, echo being the product of direct back scatter or diversion of energy to ground. Shock waves are very thin, on the order of 10^{-5} inches; their attenuation rate is only moderate, and the refractive index differences across them can be several hundred N units.

RING ECHO FROM BIRDS

9 AUGUST 1957

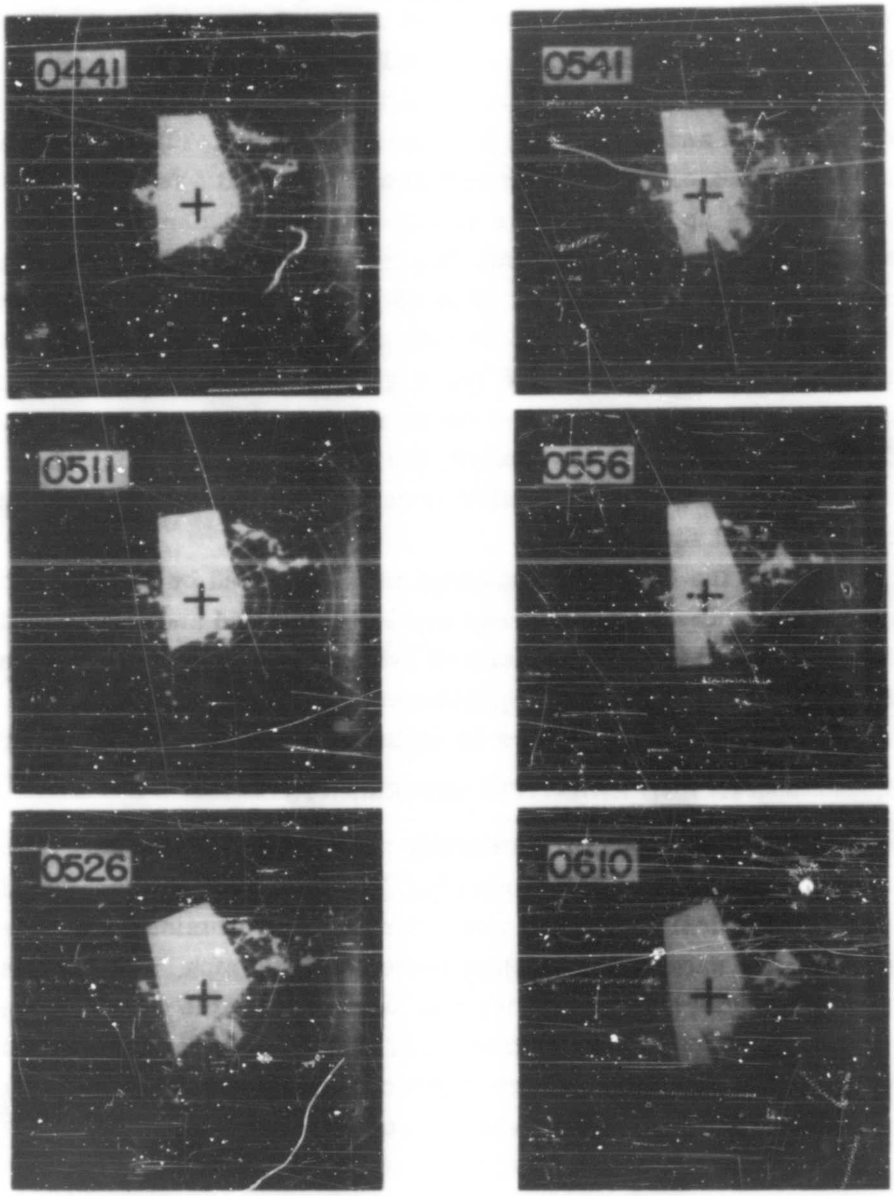

FIG. 12. A ring echo caused by blackbirds. L band. Total range is 150 nautical miles. Ground clutter echo has been eliminated. (Courtesy of Dr. M.G.H. Ligda, Stanford Research Institute.)

There are other echoes popularly termed "radar flying saucers." One explanation invokes extraterrestrial sources, but there is good reason to believe that many such echoes are merely the product of scope misinterpretation. The observer assumes that the echo return presented on successive rotations of the antenna is derived from a single moving source when actually the returns are unrelated ones of the types discussed previously. For example, a classic saucer incident over Washington, D. C. in July 1952 occurred during a period when the atmosphere was exceedingly superrefractive and "spotty" anomalous propagation was definitely in order.

Another "saucer" mechanism that explains certain rapid and erratic echo maneuvers at close range is the nonisotropic secondary scattering of energy from an aircraft to a ground object or vice versa. Phantom echoes that "overtake," "fly" parallel with, or "collide" with aircraft echoes can be explained by this mechanism, as illustrated in Fig. 13.

In Fig. 13, the heavy solid line is the path of the aircraft. The dashed line shows the echo path that would result if sufficient radar energy were scattered from the aircraft to a prominent ground object (or other reflector) located at A, and then scattered from A back to the aircraft, thence to the receiver. The dotted line is the path that results if we assume the ground object to be at B. The fine solid line assumes scattering from A to the aircraft to A to the receiver. The inward and outward excursions of this path actually occur along a single radial line passing through A; however, for illustration, each is drawn laterally displaced from its neighbor. The numbers along the paths are the elapsed time in minutes since the aircraft first entered the field of view of the diagram. The same numbers on different paths show the corresponding space positions of the echoes.

When the aircraft is the first of the two scatterers, the phantom echo always occurs at the same azimuth bearing as the aircraft and the range to the phantom always exceeds that to the aircraft. Thus, on the

PPI, the path of the phantom always lies outside the aircraft path. However, if the aircraft flies directly over the ground object, the phantom echo and the aircraft echo will almost merge, as in path C between times 12 and 13.

Conversely, when the ground object is the first of the two scatterers, the phantom echo always occurs at the same azimuth bearing as the ground object and the range to the phantom always exceeds that to the ground object. If the aircraft crosses the radial line from radar to object at a range exceeding the range to the object, then the phantom echo and aircraft echo almost merge at the point of crossing. If, however, the aircraft flies "this side" of the object, the phantom and aircraft echoes only approach as closely as that separation distance between aircraft and object at the point of crossing.

In a situation of the first kind, we can anticipate that certain RHI presentations might also be affected. For example, if a height finding radar were trained on the hypothetical aircraft of Fig. 13, a phantom echo would be observed along that radial line of the scope passing through the aircraft echo. As the aircraft was followed through various azimuth bearings, the phantom would continue to be present and would appear to be "diving" toward or "climbing" away from the aircraft. A tracking radar "locked on" the phantom would sometimes indicate very high velocities, such as the 570 mph in Fig. 13.

In a situation of the second kind, echoes would occur only if the RHI was oriented toward the ground object. The phantom would move in and out along that radial line on the scope that had the same elevation angle as the ground object.

In any actual situation, only certain portions of the Fig. 13 paths would be anticipated, preferentially those closest to the ground object. The object itself may or may not cause a scope echo; with MTI presentation it would not. The velocities of the phantom echoes are of course dependent on the aircraft velocities.

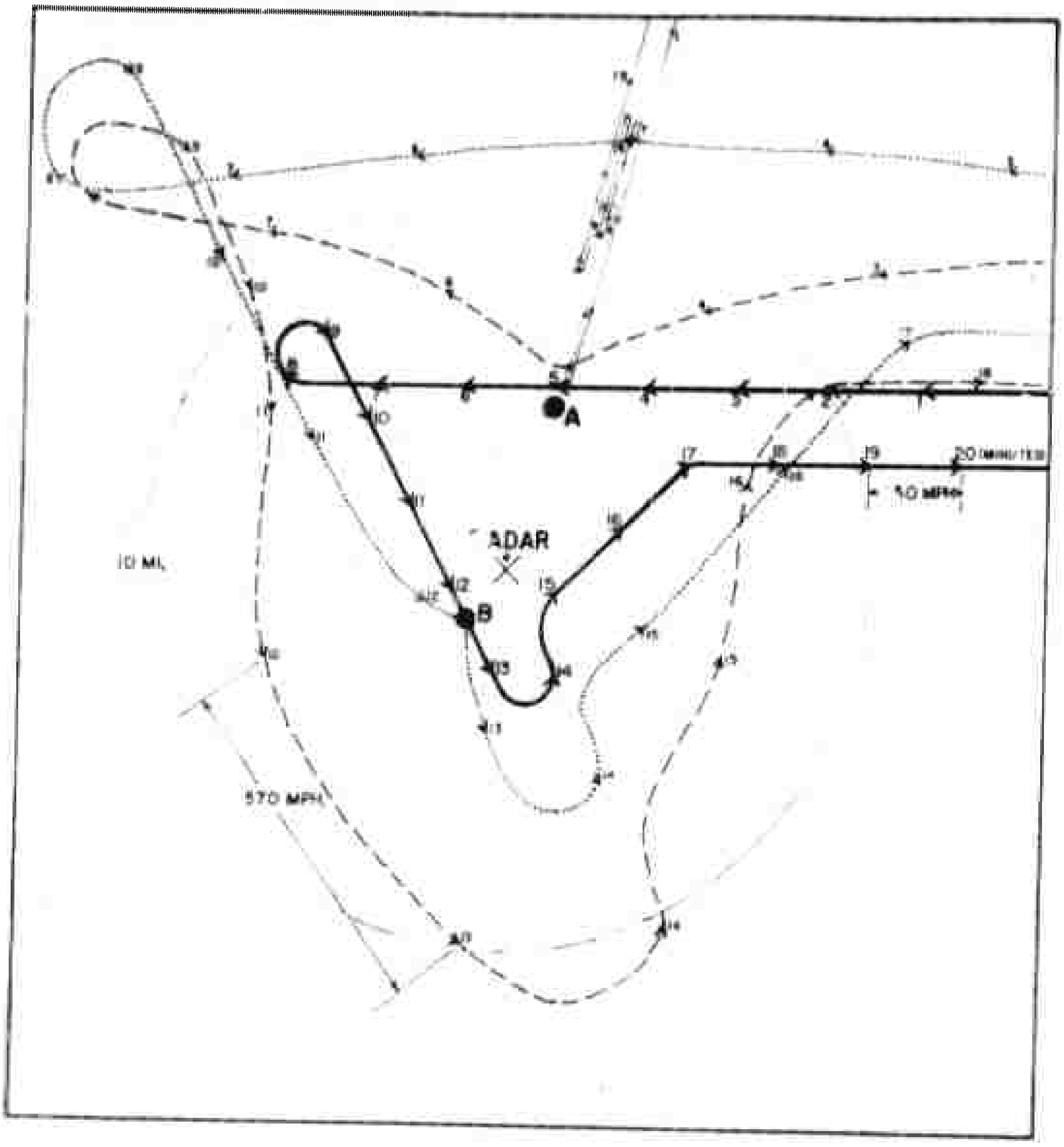

FIG. 13. Echo motions resulting from secondary, nonisotropic scattering. Heavy solid line shows path of the aircraft; numbers are time in minutes.

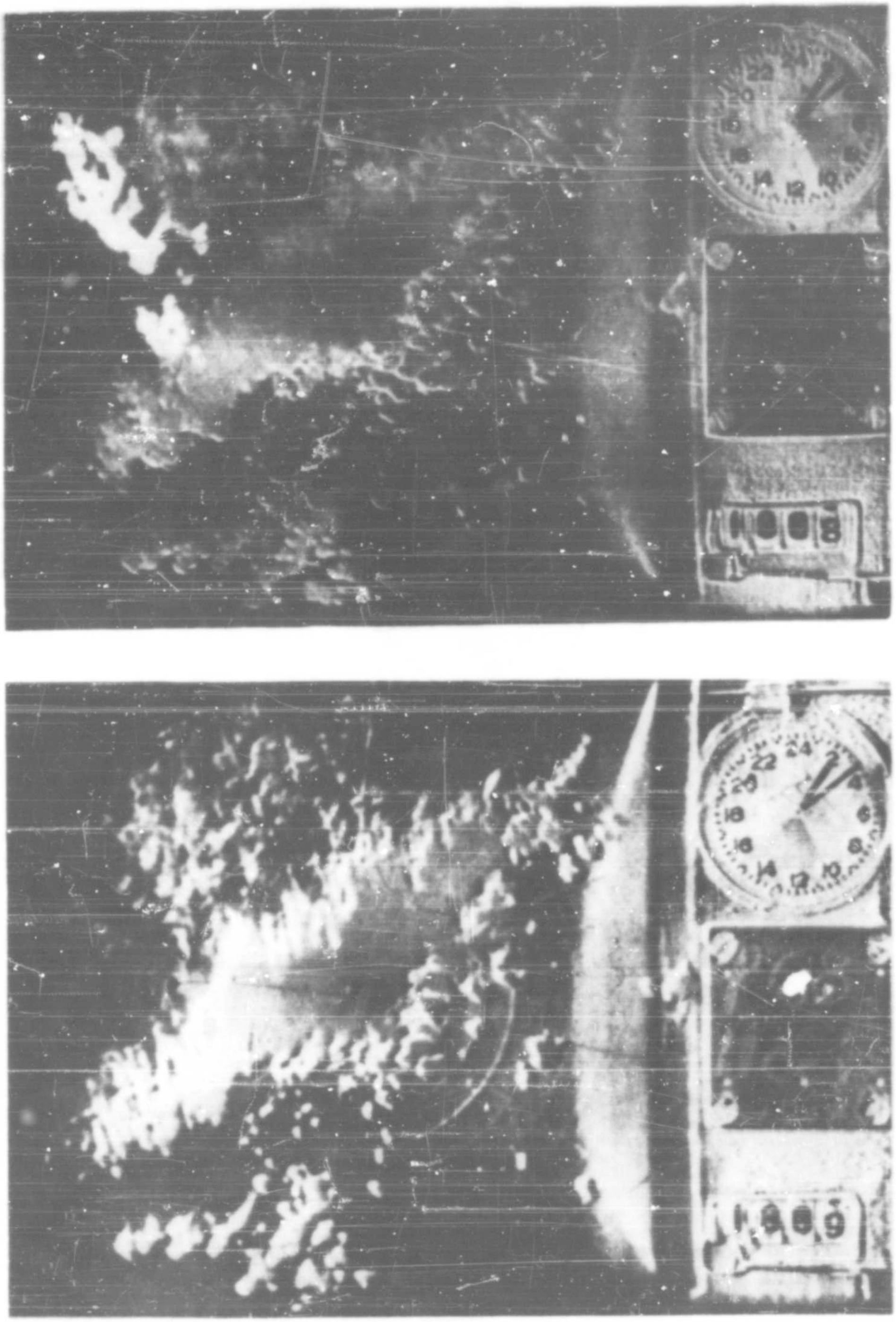

FIG. 14. L-band echo from lightning. Total range is 150 nautical miles. The echo is present on the first antenna scan but not on the next. Its length exceeds 100 miles. The precipitation echoes have been "subdued" by a process of photographic subtraction. (Courtesy of Dr. M.G.H. Ligda, Stanford Research Institute.)

9. LIGHTNING ECHOES AND SFERICS

Echoes from the ionized channels and columns formed by lightning discharges have been observed many times at X, S, and L band and VHF (for example, References 86, 94, and 99). The echoes range up to 100 miles in horizontal length, 10 miles in height, and have been detected at ranges well in excess of 100 miles. (See Fig. 14.) Most occur from heights above 20,000 feet, although echoes from discharges between cloud top (about 35,000 feet) and ground and between cloud top and the air above are not uncommon. Cellular-type precipitation echoes are invariably present on the scope when lightning is detected. Usually the lightning is observed near the cells; however, some strokes do originate from the non-echoing or weakly echoing regions of cloud and snow well away from or above the cells.

With streak lightning, the commonly observed type having a jagged forked appearance, the entire electrical event, from the initiation of the leader stroke to the termination of the return stroke and recombination of ions along the path, occurs in a few tenths of a second. With composite strokes, that is, several current pulses along the same channel, the event may persist up to 0.35 sec on the average, and 1.5 sec as a maximum.

An intense ionized channel is formed by the return stroke. This channel has a diameter of some 2-10 cm and it persists a few milliseconds before the ions recombine. If the electron densities in the channel exceed *

5×10^{8}	electrons/cm^3	at 1.5 meters	
1×10^{10}	"	"	L band
1×10^{11}	"	"	S "
1×10^{12}	"	"	X "

the channels reflect radar energy as if they were metallic. At smaller densities they scatter energy, the amount being primarily dependent on the type of ionization and the spatial distribution. The above values can

*The electron densities listed assume no effect for electron collisions. Hewitt considers this effect important; Atlas considers it small but not negligible (depending on frequency); Ligda neglects it completely.

be tied to our physical experience by noting that the threshold range for visual detection of ionization is 10^{11} to 10^{12} e/cm^3. (Loeb.[96])

A lightning channel can be a very potent radar reflector providing that the electron densities exceed the critical and that the channel is oriented approximately normal to the axis of the radar beam. Ligda[94] has computed the typical radar cross section of such a channel to be 6 square meters, or about equivalent to that of a four-engine aircraft. Such an aircraft can be tracked to 200 miles, indicating that "metallic channel" echoes are horizon limited. He also computed the probability that a perpendicularly oriented discharge of 0.5 sec duration will appear on the PPI display of a narrow-beam radar scanning at 5 rpm. About 10 percent of the strokes occurring within the volume of scan will be detected. Only a fraction of these will be completely resolved.

Ligda,[94] Atlas,[86] and others have reported that the duration of lightning strokes on radar is about 0.1 to 0.5 sec.* This is considerably longer than the persistence of the "metallic channel" ionization caused by a single return stroke and, in most cases, cannot be explained by the assumption of a composite stroke.

This discrepancy, plus observations that lightning columns at S and L band customarily have horizontal dimensions of 5,000 to 15,000 feet, led Atlas to conclude that most echoes are the result of scattering from rather extensive volumes of weak ionization. With ionization in the form of free electrons, electron densities some two to five orders of magnitude less than critical will satisfy the atmospheric electric field change requirements and account for the radar observations. Thus, the radar is able to detect many lightning discharges that are invisible to the eye.

For one particularly intense storm, Atlas was able to compare the frequency of occurrence of lightning echoes at S band with the frequency of occurrence of visual lightning. The visual observations were

*Unless the radar antenna is stationary and pointed at the storm, the radar echo is recorded on the phosphor of the scope only during a single PPI or RHI scan. See Fig. 14.

made by a cooperative weather observer who happened to be located at a point along the path of the storm. From comparisons made during much of the active life of the storm, Atlas found that the "height finder" radar, during down sweeps of the antenna, detected about 42 percent as many strokes as did the ground observer.

Utilizing his findings, Atlas also computed the probabilities that perpendicularly oriented lightning strokes, having horizontal lengths of 15,000 and 30,000 feet at 115 miles range, would be resolved by an FPS-6, S-band radar with 3° horizontal beam scanning at 20 rpm. Assuming a lightning duration of .5 sec, the probabilities are .34 for a stroke length of 15,000 feet and .31 for a stroke length of 30,000 feet. Assuming a lightning duration of .25 sec, the probabilities reduce to .17 and .13, respectively.

Lightning may affect radars in ways other than by causing echo. The discharge itself generates microwave energy that may enter an open receiver to be presented on the scope. Such energy is commonly called "sferics." Being unsynchronized with the radar, these signals are presented on the PPI or RHI as a radial line or series of dots at the particular azimuth or elevation angle of the disturbance. The signals are generally weaker and less frequent than the reflected or scattered echoes; however, with an airborne radar close to the stroke, strong signals could be anticipated.

Atlas[87] has conveniently summarized the general features of sferics. Commonly these signals are associated with the return lightning stroke and with the stepped or dart leaders preceding return strokes. However, at frequencies higher than 600 mc/sec, the radiation associated with the return stroke itself is judged to be negligibly small and most sferics signals are believed to result from the leader processes that occur in that 0.5 to 1.0 millisecond interval immediately prior to the return stroke. According to Hewitt,[91] such radiation at 600 mc/sec commonly takes the form of a long (500 μ sec) series of short (1 to 4 μ sec) noise pulses occurring at intervals of a few microseconds.

Atlas states that radiation from stepped leaders of moderate intensity may be detected by common 10 and 23 cm radars at ranges of more than 100 miles and by 3 cm radars at 10 to 30 miles.

10. SIGNALS FROM EXTRATERRESTRIAL SOURCES

Certain radars may detect signals from sources lying or originating outside the earth's atmosphere. This Section will consider the nature and probable strengths of such signals.

10.1 Microwave Emitters

The sun emits appreciable energy in the microwave region of the spectrum. Many radars have the necessary combination of antenna area and receiver bandwidth to detect this radiation and present it on the scope. Some can consistently detect the "quiet sun"; others will only receive signals on occasion, during periods of flares or low sunspot number.

Signals from the quiet sun will be readily recognized on the PPI or RHI as a small sector showing noisy return at all ranges. However, with a radar that is only capable of "seeing" the levels of energy associated with enhanced solar activity, the occasional noisy sector or sporadic echo bursts could create a problem of identification. As an aid, values of normal radiation and average maximum radiation are presented in Table 1. These values are compromises between the reports of several investigators (that is, References 101, 102, 103, 106, and 109).

An S-band radar, having an antenna efficiency of 66 percent and a receiver of 1 Mc/sec bandwidth and 100 dbm minimum detectable signal, could detect the quiet sun with a 160 ft^2 antenna. The same receiving unit could detect occasional flare activity with a 47 ft^2 antenna.

At S and X bands, solar activity is very constant. Only after intervals of days or weeks is this constancy interrupted by flares. Flare energy arrives mainly in the form of bursts lasting a few seconds, groups of bursts persisting for minutes or hours, or slow rises and falls occurring over hours or days. At wavelengths greater than one meter,

TABLE 1. **Flux densities of the sun and radio stars and circuit losses to the moon.**

Wavelength cm	Flux density observed at earth's surface watts m^{-2} (cycle/sec.)$^{-1}$			Circuit loss for round-trip to moon db
	Sun		Radio Star	
	Normal	Average max. during flares or low sun-spot number	Cassiopeia A	
1.25	18×10^{-22}	—	—	—
3.2	73 "	—	$.05 \times 10^{-22}$	—
10.7	100 "	350×10^{-22}	.1 "	-252
23	75 "	—	.3 "	-264
50	47 "	—	.4 "	-270
150	8 "	100×10^{-22}	.9 "	-278

solar output varies considerably over periods of hours, days, and months, apparently related to both sunspot and flare activity.

After the sun, the next most powerful microwave emitters are the radio stars. However, as indicated in Table 1, their energy levels are some 20-30 db less than those of the sun.[105, 107]

10.2 Aurora Borealis

Charged particles are ejected from the sun during solar magnetic disturbances. When these approach the earth some 6 to 30 hours later, they are influenced by the earth's magnetic field and they spiral inward along the lines of magnetic flux. Concentration zones for this so-called "corpuscular radiation" are centered about the two geomagnetic poles over surface areas some 3000 miles in diameter.

On descending through the upper atmosphere at altitudes between 200 and 50 miles, these high-energy particles leave long trails of ionization caused by their collisions with air atoms. The many entering particles cause extensive ion streamers and clouds. This ionization and the subsequent recombination processes produce the visual aurora.

Electron densities in the aurora may range up to 10^8 electrons/cm^3.[122] This is adequate to reflect meter waves and cause appreciable scattering of the shorter ones.[121, 122] HF and VHF propagation is greatly influenced and extensive radar displays have been observed at 44 cm and 73 cm.[44] At 73 cm, as much as 10 percent of the PPI has been covered with return, and equivalent radar cross sections range up to 3000 m^2. Echoes should be possible at 23 cm and, as sensitivities increase, effects could also be anticipated at S band.

Radar echoes from the aurora occur primarily under the condition that the radar is nearly perpendicular to the ion streamers, that is, to the magnetic lines of flux. For a radar in the temperate zone pointed in the general direction of the geomagnetic pole, this condition exists at a different range for each azimuth and elevation angle. A single three-dimensional surface of perpendicularity exists for each radar site, perhaps extending over some 20° to 50° in azimuth and 1° to 7° in elevation. A method of specifying these surfaces has been developed by Fricker, Ingalls, Stone, and Wang.[44]

Observations at 73 cm show that echoes are still received when the beam deviates by as much as 3° from perpendicualr. This means that the echoes are received from a range depth of about 300 miles. Numerous discrete echoes occur within this interval and most of them evidence considerable variability in intensity, space position, and time continuity.

Besides being a complex function of antenna orientation, the range to the reflecting zone usually exceeds the maximum scope range. Thus, the scope echoes are multiple sweep ones and they may occur at any range in the auroral quadrant. They may be large or small, diffuse

or distinct, moving or stationary. In general, the echoes will be more discrete and more variable at the shorter wavelengths and on those radars having only a marginal capability for detection. A cosecant-square antenna will cause the echoes to be larger and more diffuse.

During auroral periods the observed echoes are most frequent at night. A maximum should occur 1.3 hours before magnetic midnight.

10.3 The Moon

Under certain operating conditions very sensitive radars may receive echoes from the moon (for example, References 112, 113, 117, 118, and 119).

The moon is a nearly spherical body some 2160 miles in diameter and it moves in an orbit about the earth at a distance that varies from 221,463 miles to 252,710 miles during the period of approximately one month.

Since the surface of the moon has many craters and mountains, we would expect that radio waves would be scattered from all irregularities over a depth equal to the moon's radius and that incident radar pulses shorter than the diameter would show an appreciable lengthening after reflection. However, this is not the case. Due to some peculiarity of its valley and plain areas, apparently smooth lava understrata covered by fine dust, the moon is almost a specular reflector.

Long pulse signals returned at wavelengths of 10 cm to 11 meters persist about 1 millisecond, showing that just the near spherical cap of the moon reflects appreciable energy.* This cap has a base diameter of some 900 miles, a depth of 100. The first 50 percent of the reflected power is returned from a small "highlight" about 200 miles in diameter.

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*In the radar equation the moon circuit loss is $\sigma \lambda^2/(4\pi)^3 r^4$. The reflectivity of the moon is included in σ. σ is the equivalent radar cross section, λ is the wavelength, and r is the range to the moon.

In the microwave region, the radar cross section of the moon varies from about 10^5 ft^2 to 3.5×10^5 ft^2. The circuit losses between an isotropic radiator on the earth to the moon and back to an isotropic collector are shown in Table 1.[117] These losses apply for 10 μ sec pulses and beam widths that completely illuminate the moon (the moon subtends 0.5°). For shorter pulses the losses increase by roughly 2 db for every microsecond that the actual pulse is less than 10. An L-band radar with P_t = 1 Mw, $P_{r_{min}}$ = -110 dbm, h = 5μ sec and $G_t = 10^4$ would receive a moon signal some 6 db above noise, ignoring system losses. (P_t = transmitted power; $P_{r_{min}}$ = minimum receivable power; h = pulse length; G_t = gain of transmitting antenna.)

Moon echoes will not be detected unless the radar is fixed in the moon direction or unless the scanning program has some accidental or systematic periodicity that returns the antenna to the moon direction every 2.4 to 2.7 seconds. This might occur in sector scan, RHI scan, or during tracking.

At 10 cm with 2 μsec pulses, the observed moon echo is composed of a number of individual spikes, each some 2 to 4 μsec wide separated by 2 to 20 μsec from its neighbors.[119] The most intense part of the echo occupies 100 μsec, although sporadic structure may be observed over 400 μsec. The scope picture at RHI or sector scan would probably show a number of discrete echoes at variable range occupying a small sector.

Radio-radar waves from other sources may reflect from the moon and enter the receiver to be presented as noise. The sources could be well over the horizon.

10.4 Meteors

Meteors enter the dome of the sky above a radar site with the approximate frequency shown in Table 2. Approaching at velocities of 25,000 to 160,000 mph, these particles become incandescent at altitudes of 100 to 60 miles and, unless they are larger than 8-cm radius, they

TABLE 2. Sporadic-meteor sizes, average frequency of occurrence, typical electron densities in trail, and probabilities of interception.*

Radius of Meteor	Number, indicated size or larger, entering dome of sky per day	Electron densities in trail immediately behind meteor	Electron densities in trail one second after passage	Probability of interception with a 4° beam in PPI scan at 5 rpm	Probable level of radar detectability
cm		electrons/cm^3	electrons/cm^3	number/day	
8	7×10^{-1}	$>1 \times 10^{14}$	$>3 \times 10^{10}$	2×10^{-3}	
4	" 10^{0}	" "	" "	" 10^{-2}	
2	" 10^{1}	" "	" "	" 10^{-1}	
.8	" 10^{2}	1×10^{14}	3×10^{10}	" 10^{0}	X band
.4	" 10^{3}	" 10^{13}	" 10^{9}	" 10^{1}	S band
.2	" 10^{4}	" 10^{12}	" 10^{8}	" 10^{2}	L band
.08	" 10^{5}	" 10^{11}	" 10^{7}	" 10^{3}	
.04	" 10^{6}	" 10^{10}	" 10^{6}	" 10^{4}	
.02	" 10^{7}	" 10^{9}	" 10^{5}	" 10^{5}	

*Basic data providing electron line densities and the incidence of meteors for the entire atmosphere was obtained from Eshleman.[123]

have completely disintegrated by the time they reach 25 miles. While passing through these altitudes the meteor particles literally boil away, leaving an intense trail of ionization. Immediately behind the particle the trail is 2 to 20 cm in diameter; about 1 second later (or some 40 km behind) the trail has expanded by molecular diffusion to some 4 meters, and thereafter it expands at an accelerated rate due to atmospheric turbulence.[121, 122]

Electron densities in the trails are also indicated in the table. Referring to the critical densities required for metallic-like microwave reflection (page 29), we see that all meteors larger than 0.04 cm have sufficient trail density to reflect L-band microwaves. Those larger than 0.08 cm will reflect S band, and those larger than 0.2 cm will reflect X band. One second after meteor passage, only those trails formed by larger than 0.8-cm particles will still reflect L band, and the corresponding values for S and X bands are 2 cm and about 4 cm. With further aging, the trails lose the ability to reflect, but they retain the ability to scatter primarily because of electron inhomogeneities created by turbulence.[122]

Considering a 0.1 second, or 4-km length of one of those trails with above-critical electron density, the total cross section is some 600 m^2. However, this cross section will not be an effective reflector unless the trail is oriented very nearly perpendicular to the radar beam, the so-called radiant condition. For trails not perpendicular the signal returned to the radar will depend primarily on the scattered signal associated with turbulent breakup of the trail.

Considering the electron densities in Table 2, the critical levels for reflection, and the necessarily great range to the trails, it seems justifiable to conclude that only about 25 percent of those trails intersected by the radar will be detectable at the wavelength levels shown. The probability of detecting a trail is very small. Even at L band, only 0.25 x 200, or 50 meteor echoes would occur per day. As with lightning, they would be present for only a single scan and, since

they would ordinarily be multiple sweep echoes, they could occur at any range.

11. FUTURE OUTLOOK

Angel observations have provided the meteorologist with an insight into some heretofore unsuspected inner workings of the atmosphere; but the full potentialities of radar techniques for studying such things as fronts, inversions, lightning activity, and the processes of convection are just beginning to be realized. For example, vertical probing at L and P bands, as suggested some eighteen years ago by Friend,[10] should enable us to detect and monitor the positions of certain fronts, clouds, and inversions and thus obtain information not presently available from weather radars that depend on particle scattering for signal. The technique should also interest those concerned with trans-horizontal radio propagation, for chances are that the atmospheric structures that cause echo at 90° incidence are also important in the diversion of energy over the horizon at lower incidence angles.

To operational radar people and set designers, angels constitute a problem of severity dependent on wavelength and range capability. Unidentified scope echoes necessitate warnings to pilots or perhaps the dispatch of interceptors. Their elimination is very much desired. Effort is presently being devoted to this attempt and there is hope that certain echoes can be eliminated; but the problem will be with us for some time to come. There is a great need for detailed observations of the echo characteristics so that we can eventually discover the Achilles' heel.

Before we can truly say that we understand atmospheric angels, we require direct, high resolution measurements of the physical structure of the echoing volumes. At the same time, electromagnetic theory must be extended to explain the processes of energy return from dielectric inhomogeneities. In this regard, a very promising theory has

recently been advanced by Atlas.* He postulates that the radii of curvature of atmospheric inhomogeneities are so large that the theory of the "near zone" must be used when considering energy return. His equations, based on this theory, predict the signal strengths normally associated with angels from reasonable assumptions concerning inhomogeneities of the types described herein.

*D. Atlas, "Possible Key to the Dilemma of Meteorological Angel Echoes., J. Meteor. Avail. 1959.

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